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FAILURE ANALYSIS AND ACCIDENT INVESTIGATION ACTIVITIES AT NAL

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Abstract: Failure is an undesirable and unacceptable event in the service life of a component or structure. But in spite of the fact that utmost care is taken in the design and manufacture of components, many examples of service failures of engineering components are around us. While failures can be tolerated in non critical areas, where they would be more of an inconvenience, they cannot be allowed to occur in critical, high technology areas such as nuclear engineering, aerospace technology, power plants, etc. However, when such failures do occur, they provide an opportunity to identify deficiency areas and initiate remedial measures to prevent recurrence of the same. Failure analysis therefore provides the best tool for improving the reliability and safety of engineering components and structures.

This article gives an overall view of failure analysis as a discipline and highlights NALs contribution in advancing the state of the art. The article is illustrated with numerous examples taken from case histories of failures and accidents investigated at NAL.

Keywords : Failure analysis, service life

1. INTRODUCTION

In recent decades, the demands of space limitations and increased loads, particularly in the aircraft industry, have accelerated the trend towards utilisation of high strength and ultra high strength materials. These high strength components are also required to perform under extreme conditions of temperature, stress and environment, as for example, in a modern jet engine. When corrosion and stress, static or cyclic, occurs simultaneously, particularly in high strength metals, the possibility of failure becomes more pronounced. Although fail safe design philosophy based on damage tolerant structures has come into existence and quantitative methods of nondestructive, in-service detection of flaws is available, failures of aircraft components and catastrophic accidents to aircraft is a common occurrence. Such a probability of failure exists because of the many unanticipated and unforeseen factors due to the variabilities in the structural reactions of a metal. Significant changes in mechanical behavior occur due to processing operations, field repairs, adverse or unforeseen loading and environment or deterioration with time and temperature or operating conditions. It is only by a systematic analysis of failures that a careful sorting of these factors can be attempted to determine how and why a metal part failed.

Service failures of engineering components and accidents have great impact on society and its economy. Failures and accidents lead to loss of machine time, loss of production and above all, loss of human lives in many instances. Because of failures and accidents, the product liability insurance premia have increased to a point at which they have become a major business cost in industries in some countries. Further, as the complexity of our technological systems increase, so do the possible consequences of service failures. Because of the strategic nature and costs involved both in terms of equipment and trained manpower, there is a strong necessity to fully analyse any failures occurring in aircraft, spacecraft and missiles, so that the reliability of the system could be improved.

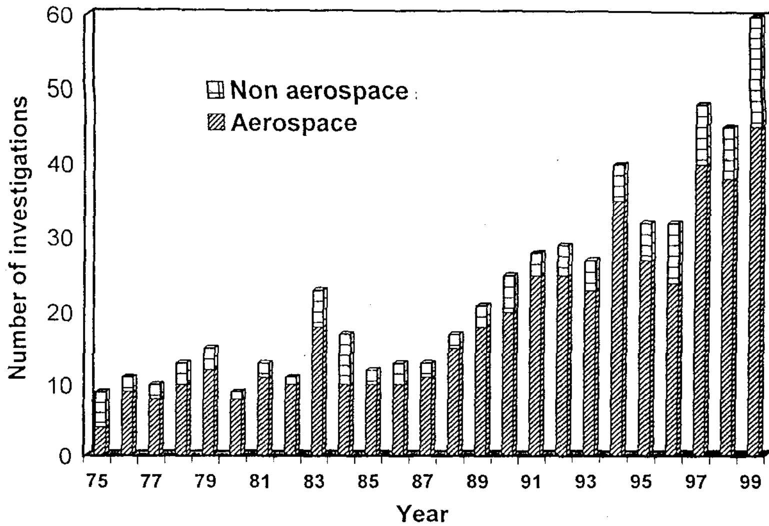

Fig. 1. Year wise progress of failure analysis

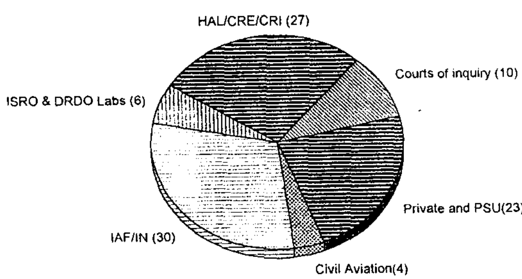

Fig. 2. Organizations assisted by failure analysis group, NAL.

The failure analysis group at the National Aerospace Laboratories (NAL), Bangalore, has, over the years, built up the necessary infrastructure and expertise to fulfil this task. NAL has also the advantage of being a multidisciplinary engineering laboratory where expertise from several related fields is available under one roof. NAL has so far investigated over five hundred service failures and major aircraft and industrial accidents and has also participated in several major investigations with international agencies like Rolls Royce, Pratt & Whitney, Boeing and Airbus industry. The enclosed bar chart (Fig.1) gives the progress of the failure investigation activity at NAL. Almost all the aerospace organisations and several public and private sector organisations in the country have been assisted. The enclosed sector chart (Fig.2) gives a split of the organisations assisted.

2. TYPES OF FAILURES IN METALLIC COMPONENTS

Service failures of engineering components can be generally classified into four main categories. These are.

1. Mechanical failures

* Ductile and Brittle failures
* Fatigue failures
* Distortion failures
* Wear failures

2. Environmental failures

* Corrosion Failures

* Liquid Erosion Failures

3. Mechanical-environmental failures

* Stress Corrosion Cracking
* Hydrogen Embrittlement
* Liquid Metal Embrittlement
* Corrosion Fatigue

4. Thermal failures

* Creep
* Stress Rupture

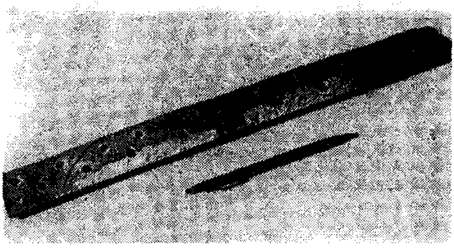

Fig. 3. Exfoliation Corrosion attack on 2024 aluminium alloy spar cap.

Fractures either of the ductile or brittle type under static loads are rare in service since they are taken care of by the designer by providing adequate factor of safety. Fatigue is an important phenomenon in the design of engineering structures and components since failures in fatigue take place under normal and what are considered safe working loads and not under abnormal loads as in static, overload failures. Fatigue failures account for over 80% of all failures in aircraft structural components. Fatigue failures can be of low cycle or high cycle type and can also occur under thermal or corrosive environments. Corrosion can manifest itself in several forms but from the failure analysts point of view, pitting corrosion and intergranular corrosion are of significance. Exfoliation corrosion is a special form of intergranular attack that primarily affects aluminium and magnesium alloys. It is markedly directional and is characterised by attack of the elongated grains on a plane parallel to the rolled, forged or extruded surface. This results in the characteristic delamination or destratification of the surface layers. Figure 3 shows a 2024 aluminium alloy extruded spar cap affected by exfoliation corrosion.

Mechanical-Environmental fracture of engineering metals refer to cracking of metals and alloys under the conjoint action of a stress and a corrosive environment. It has an enormous impact in many diverse segments of the economy such as power generation, chemical, petroleum, petrochemical and mineral processing, transportation etc, and is usually the limiting factor to advancing the state of the art. The two important environment assisted failures in metallic components are stress corrosion cracking and hydrogen embrittlement.

Among thermal failures or elevated temperature failures the most commonly encountered phenomenon are creep and stress rupture, thermal fatigue, general oxidation and carburisation and hot corrosion. Hot corrosion of nickel base and cobalt base alloys is accelerated oxidation. This is caused by molten sulfur bearing slag forming on the surface of the engine components, fluxing the normally protective oxide scale on the surface of the alloy. Blades affected by hot corrosion show the characteristic swelling, together with splitting and flaking along the leading and trailing edges of the airfoil.

3. COMMON CAUSES OF FAILURES

Metallic components in service can fail due to a variety of causes. These are related to its design, manufacture, assembly, inspection, operation and maintenance.

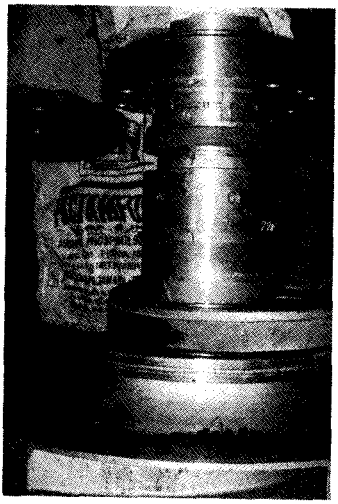

Fig. 4. Failed, motor driven pump of a fertilizer plant.

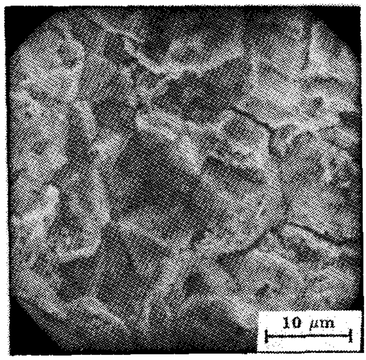

Fig. 5. Intergranular features, typical of hydrogen embrittlement, seen on the fracture surface of the failed screw.

3.1 Design

Inadequate or faulty design is often at the root of premature failures in components. These include underestimation of stress, undesirable geometry like too sharp a fillet radius or inadequate clearances, improper choice of materials and heat treatment processes and inaccessibility of parts for inspection.

There was failure of a motor driven pump in a fertiliser plant (Fig.4). The pump failed during operation resulting in extensive damage to several components. Dismantling of the failed pump showed fracture of the shaft and extensive damage to throat bushes and sleeve nuts. Pieces of metallic debris were recovered from the non-driven end throat bush region. Observations and laboratory tests revealed that these metallic pieces had originated in-situ from the interface of the nitronic bush and the stellite inlay on the sleeve nut due to adhesive wear, that is, constant rubbing of the rotating sleeve nut with the stationary throat bushing. The loose particles thus generated had choked the clearances and caused frictional heat and ultimate seizure leading to fracture of the shaft and other damages observed. Insufficient clearance between the throat bush and the sleeve nut was identified as the cause for the adhesive wear.

Specification gave a clearance on diameter as 0.8 mm. It was suggested that it would be advisable to specify the minimum clearance in static condition at the bottom side of the shaft. It was also suggested to take into consideration the possibility of shaft deflection while running. Based on these recommendations a design review was undertaken and the problem was overcome by providing the necessary clearances.

3.2 Manufacture

Imperfections, abnormalities and other deficiencies can be introduced in material by primary fabrication processes such as casting, forging, welding, machining and thermal and surface treatments. These can cause premature failure of components in service.

Improper surface treatments are known to cause service failures in engineering components. Electro plating, commonly employed as a form of surface protection, has often led to hydrogen embrittlement because of improper processing or improper post plating treatment. Max screws are used in fuel injection pumps of automobiles. These screws, made of high strength steel are zinc plated, passivated and tempered. Some

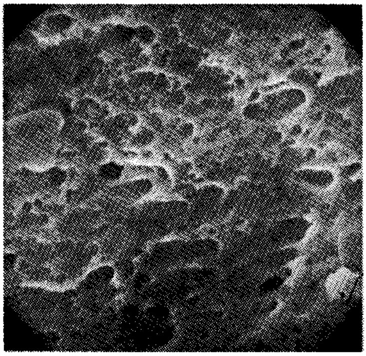

Fig. 6. Elongated shear dimples typical of torsional overload seen on the fracture surface of the failed link.

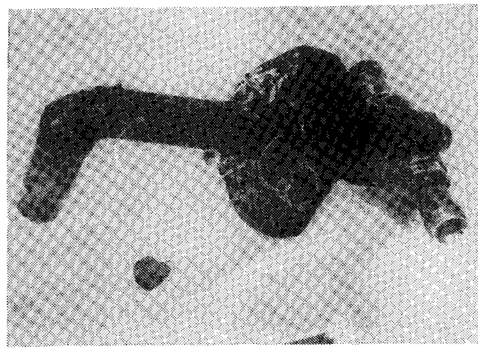

Fig. 7. The burnt fuel nozzle.

screws had failed at the assembly stage. Laboratory investigations revealed that the cracks had originated at thread roots and progressed inwards. Gross fracture features were typical of brittle failure. Under the scanning electron microscope intergranular fracture mode with partially formed dimples on the fracture facets was observed (Fig.5). The hardness of the screw was measured and found to correspond to 43-45 HRC as against the specified hardness of 33-39 HRC.

Fractographic features clearly indicate hydrogen embrittlement as the cause of failure of the screws. Hydrogen embrittlement is a common problem in high strength steels that are plated for corrosion resistance. Hydrogen enters the steel during plating and/or during pickling prior to plating and embrittles the steel leading to its cracking during service. Higher hardness (strength) increases the materials susceptibility to embrittlement. A baking treatment immediately after plating, as per recommended standards, will avert this problem.

3.3 Assembly

The common assembly defects that lead to failure are assembly stresses, improper tightening, improper alignment, improper balancing and wrong assembly.

An Aileron control linkage of a pilot less target aircraft (PTA), made of steel, failed during test and assembly. The control link had failed at a thread root. Spiral like deformation marks and shear dimples on the fracture surface (Fig.6) confirmed torsional overload as the cause of failure. At the region where the linkage was bolted, one of the threads was wrenched and pulled out indicating excessive torque. This is a case of failure due to improper tightening. The use of proper torque wrenches and exercise of care to see that the linkage is not over-torqued is an obvious solution to this problem. It was also suggested that the diameter of the threaded ends be increased. This will go a long way in overcoming failure.

During a test flight of a four engine aircraft, warning signal for fire on one of the engines appeared. Following the failure of on board fire fighting exercises, the aircraft made a safe three - engine landing. However, the fire warning remained on till the aircraft power was switched off. Strip examination of the engine revealed burning of hoses and rubber gaskets. On re-start of the engine after rectifying these defects, it was observed that fuel was leaking extensively from the base of main fuel burner. It was found that the burner was fitted facing the compressor end and not the turbine end. Such a fitting can stabilize a flame around the nozzle. Fig 7 shows the damaged nozzle of the burner fitted facing the compressor end. The nozzle had been exposed to flame both at the flange end and the atomizer end. At the atomizer end, the nozzle had melted and solidified. Detailed

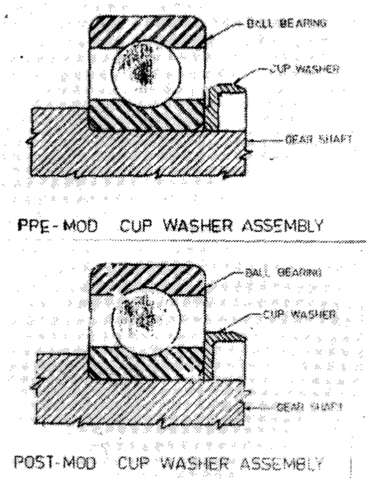

Fig. 8. The pre-mod and post-mod versions of the locking cup washer.

metallurgical investigations revealed that the steel nozzle had experienced high temperature of the order of melting point of steel. Though this is a case of wrong assembly of the burner, it also points to inadequate design since human error can inadvertently lead to a wrong fitment of the burner.

3.4 Inspection

Use of wrong inspection techniques and non calibration of instruments have often caused major failures. During ground run, one of the four oil sumps of an aircraft pneumatic system burst. Analysis of pieces from the wreckage clearly indicated high strain rate fracture under shear stresses. Since no pre-existing crack or corrosion was responsible for the cylinder burst, it was recommended that the pressure control valves should be examined for proper operation and also it should be established whether the pressure gauge was properly calibrated.

3.5 Operation

A number of failures can be attributed to this factor. Among these are inadequate lubrication, non adherence to inspection schedules and non conformity with operating instructions like over speeding, high operating temperature, overloading and use in environment not intended for the purpose.

3.6 Maintenance

Proper maintenance is as important as any other factor contributing to the successful functioning of a mechanical system. Some of the maintenance problems that have resulted in failure are wrong replacement, application of wrong tools, inadequate inspection before re-use and ad-hoc alteration.

Bearing failures were encountered in the supercharger gearbox of an aircraft. These bearings are lubricated by a jet of oil. There had been a modification in the design of the locking cup washer and all the failures had occurred in the post mod version (Fig 8). The failure of bearings was due to lubricant starvation as a result of the modification. Roller bearings had got kneaded into spherical shape. This case amply illustrates the ill effects of ad-hoc alteration of design.

4. METHODOLOGY OF FAILURE ANALYSIS

The role of failure analysis is

- To determine the mechanism by which the failure took place (Fatigue, SCC, Hydrogen embrittlement, Creep etc)
- The mechanism of final rupture (Dimple rupture, Cleavage)
- Whether or not material defects (Inclusions, Porosity, etc) or design and manufacturing defects (Notches, Scratches, etc) were involved and,

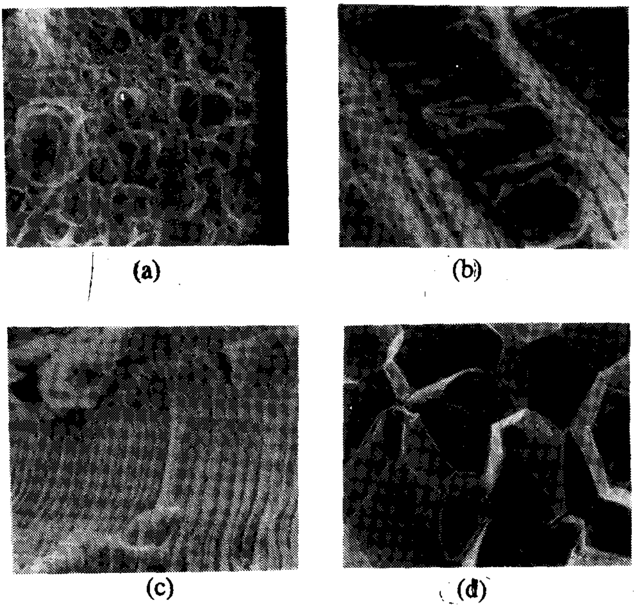

Fig. 9. Some common fractographic features seen on laboratory tested samples. (a) Dimpled rupture in ductile fracture. (b) Cleavage facets in brittle, transgranular fracture. (c) Striations in fatigue. (d) Decohesive or intergranular rupture in environment assisted fractures like Stress corrosion cracking/Hydrogen embrittlement.

- Whether or not service abuse or environmental factors played a role in the failure process.

To fulfil this role, failure analysis has to be conducted in a systematic manner. Well established methodologies exist to carry out the same.

4.1 Stages of an analysis

Although the sequence is subject to variation depending upon the nature of a specific problem, the principle stages that comprise the investigation and analysis of a failure are

- Collection of background data and selection of samples
- Preliminary examination of the part
- Nondestructive testing
- Mechanical testing
- Selection, identification, preservation and /or cleaning of specimen
- Macroscopic and Microscopic examination and analysis
- Observation and analysis of metallographic sections
- Chemical analysis
- Determination of failure mechanism
- Fracture mechanics considerations
- Analysis of all evidence, formulation of conclusions and writing of the report

The extent to which the above stages are applicable is dictated by individual cases. However, fractography, which is the science of study of fracture surfaces, is widely used in all failure investigations and is often called the corner stone of failure analysis. Fractography is generally conducted at two levels of magnification termed as macrofractography (with the unaided eye or low power magnifier) and microfractography (with the help of a microscope). Fractography depends on the principal that whenever a component fails under load it leaves certain markings behind. These are called signatures of fracture. Identifying these signatures is a vital step in failure analysis.

Fracture initiation and propagation produces certain characteristic marks on the fracture surface. Some of these are fibrous marks in ductile fracture, radial lines and chevron marks in brittle fracture and half moon shaped marks, familiarly called beach marks, in fatigue. These marks indicate the direction of crack growth. The analyst traces these features backward to find the origin or origins of fracture. Macrofractographic features are often insufficient to properly evaluate fracture modes. Stress corrosion cracking and fractures involving corrosion cannot be conclusively identified through macroscopic examination alone. Also, material abnormalities showing up on the fracture surface tend to complicate macroscopic examination thus requiring microfractographic examination.

Examination of the fracture surface with the electron microscope, particularly with the scanning electron microscope is, in some instances, the only effective way of defining the fracture mode and mechanism. Some of the well documented electron fractographic features are dimples (Fig.9a) in the case of ductile fractures, cleavage facets (Fig.9b) in the case of brittle fractures, striations (Fig.9c) in the case of fatigue and decohesive or intergranular fracture (Fig.9d) in the case of stress corrosion cracking.

Proper documentation and analysis of macro and micro fracture features helps in identifying the fracture mechanism.

4.2 Mechanical testing and Metallography

Once the mechanism of fracture is known, it becomes necessary to determine the cause or causes leading to the failure. This necessitates mechanical property evaluation and metallographic studies. Both of these are destructive in nature and needs a suitable system of sampling. A variety of mechanical tests are performed on specimen taken from failed components to determine whether the components conform to specified strength values. Where appropriate, tensile, fatigue or impact tests should be carried out provided sufficient material is available. Hardness testing can be used to assist in evaluating heat treatment, to provide an approximation of tensile strength of steel and to detect softening or hardening caused by overheating. The failure analyst should exercise care in interpreting mechanical test data.

Metallographic investigations which are also destructive in nature are seldom performed on the fracture surface. A suitable system of sampling is therefore necessary before conducting metallographic studies. These studies give an indication of both gross and microscopic features of the material and helps the analyst in arriving at valid conclusions regarding the failure.

4.3 Analysing the evidences, Formulating conclusions and Writing the report

After collecting all the evidence as described above it would be relevant to pose and answer the following questions before formulating conclusions.

- Has the failure sequence been established?
- If failure involved cracking or fracture, have the initiation sites been determined?
- Was cracking associated with a stress concentrator?
- What was the failure mechanism?
- What was the approximate service temperature at the time of failure?
- Was the proper material used?
- Was the component that failed properly fabricated, properly heat treated and properly assembled?
- Was the failure related to improper maintenance or abuse in service?
- Can the design of the component be improved to prevent similar failures?

In general, the answers to these questions will be derived from a combination of factors including the examination of records and examination of the tests already described. Where cause or causes cannot be determined with certainty, it will be necessary to determine the most probable cause or causes of failure.

The failure analysis report should be written clearly, concisely and logically. A report containing the following details will generally be representative and adequate.

* Description of the failed component

* Service condition at the time of failure

* Prior service history
* Manufacturing and processing history of component
* Mechanical and metallurgical study of failure
* Summary of mechanisms that caused failure
* Recommendations for prevention of similar failures

5. CASE HISTORIES

A brief description of the types, mechanisms and causes of failures in metallic components is presented above together with the methodology to be adopted in analysing failures. Five case histories are highlighted below to demonstrate how the principles and methodologies of Failure Ananlysis can be applied to solve practical problems. The five cases illustrated are

(1) Cracking of underwater luminaires due to stress corrosion cracking

(2) Cracking of 2062 grade B shell plates of storage tank of a petroleum refinery due to hydrogen embrittlement

(3) Failure of Low Pressure Turbine disc of an aeroengine due to non adherence to design specifications

(4) Failure of main wheel hubs of an aircraft due to fatigue

(5) Failure of center support bearings of a jet engine due to overheating caused by misalignment

5.1 Cracking of underwater luminaires

5.1.1 Background data :

A leading lighting company which manufactures various types of lamp sources and luminaires had developed special luminaires for application in musical fountains. Some of these luminaires installed in musical fountains were cracking up after short periods of use. Since the company had already manufactured a number of these luminaires, it was necessary to see whether the remaining luminaires could be retrieved for use without the problem of cracking. Two of the cracked luminaires were analysed to determine the Cause of cracking and suggest methods of retrieval of the remaining parts.

The luminaires are made of Brass (Cu 63.5% ; Zn 36.35%) and are produced by deep drawing and spinning. They are subsequently finished by turning. It was reported that the water in the pool was hard water.

5.1.2 Observations :

Visual: Fig 10 shows the two cracked luminaires brought for investigation. Arrow indicates the crack seen on the body of one of these luminaires. Cracks were seen on the body of both the luminaires and the metal was found bulged outward in the region of cracking.

Optical Microscopy: A suitable sample incorporating the edge of the crack was cut from the body of the luminaire, metallographically prepared, etched in alcoholic ferric chloride

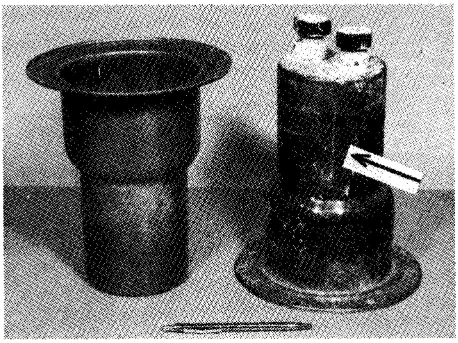

Fig. 10. The two cracked luminaires received for investigation. Note the crack indicated by an arrow.

and observed in an optical microscope. The crack path was intergranular with significant branching. The microstructure was typical of cold worked, single-phase brass.

Scanning Electron Microscopy: Under the scanning electron microscope cleavage like features with grain boundary cracking was seen. The material was semi-quantitatively analysed by EDAX and found to conform to specifications.

Discussion : The nature of cracking seen in the material is typical of stress corrosion cracking. Stress corrosion cracking is common in brass components and is familiarly called season cracking in brasses. For season cracking to occur, three conditions are necessary. (1) A susceptible material, (2) Corrosive environment and (3) Presence of tensile stress (Residual and/or applied) above some threshold value. In the present case it is seen that the material is in a cold worked state as indicated by the elongated grains. Cold working normally introduces surface residual tensile stresses. The presence of residual stress is corroborated by the sheet metal bulging and springing back at the region of cracking. The hard water in which the luminaires are immersed provide a conducive environment for stress corrosion cracking.

Conclusion : The luminaires have failed by stress corrosion cracking.

Recommendations : The following remedial measures were suggested to retrieve the manufactured components for further use and also to overcome the problem of cracking in future applications. (a) The finished components should be stress relief annealed at 260C-280C for 30 minutes. This will eliminate the residual stresses. For all future applications, components after deep drawing should be subjected to similar treatment. (b) Surface protection layers can be applied to the components in the form of some organic base waterproof paints.

The manufacturer overcame the problem after implementing these recommendations.

5.2 Cracking of IS- 2062 grade B shell plates of storage tank

5. 2. 1. Background data : A major Refinery and petrochemicals plant faced cracking of IS-2062 grade B material (C 0.14, Mn 1.05, Si 0.21) used for the shell plates of storage tanks. Both 20mm and 18mm thickness plates are used in the fabrication of the tanks but it was reported that cracking was predominant in the 20mm plates, the incidence of cracking in the 18mm plates being isolated. It was found that cracks were developing at right angles to the weld in the plate material (base material) a few days after welding. Site investigations also showed that the problem was peculiar to a particular cast number. Many plates belonging to this cast number showed transverse cracks after welding. NAL was requested to undertake investigation into the cause of cracking so that an in-situ weld repair procedure could be evolved to prevent future failures.

5.2.2 Observations :

Visual: Fig 11 shows a cracked plate sent for investigation. All the cracks were at right angles to the weld (transverse cracks). Visually, the cracks were found to emanate from the base metal, close to the weld. Some of the cracks were through thickness and the cracks were of varying lengths. When some of these cracks were opened for further

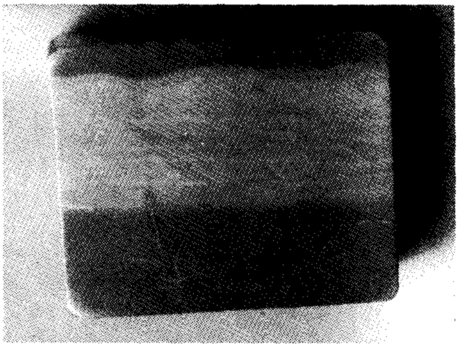

Fig. 11. The cracked shell plate of a petroleum storage tank.

examination, it was seen that the fracture surfaces were discoloured by corrosion. Gross features of fracture were brittle in nature.

Optical microscopy: Microstructural studies on polished and etched sections showed a banded structure (alternate bands of ferrite and pearlite aligned in the rolling direction). The cracks were transverse to the rolling direction and the crack path was transgranular with little crack branching. Presence of gas porosity was also seen.

Scanning microscopy: Under the scanning microscope, cleavage fracture with feathery markings and isolated dimples was seen.

Chemical composition: Spectrographic analysis was conducted on suitable sample pieces taken from the plate to determine the chemical composition of the plate material. It was seen that the composition largely conformed to specifications except that the silicon content was found to be higher than the specified value. However, this does not have any bearing on the cracking of the plate.

Mechanical property evaluation: Tensile tests and hardness measurements were conducted on standard samples taken from both the 18mm and 20mm plates. The results are given in the table below.

	Hardness - VPN, 1.0 cm away from the weld (1 Kg load)	UTS (MPa)	% Elongation
18 mm plate	204	454	39
20 mm plate	246	545	36

Discussion : Gross and microscopic features of fracture indicate brittle type of failure. Since the steel in question has a ductility of about 35%, brittle fracture is possible only when there is an embrittling agent. Fracture features like cleavage and feathery regions point to hydrogen as the embrittling species. In hydrogen cracking, also called cold cracking, the fracture is either intergranular or transgranular cleavage. Cold cracks are defects that form as the result of contamination by hydrogen. Whereas solidification cracking and heat affected zone (HAZ) cracking occur during or soon after the actual welding process, hydrogen cracking is usually a delayed phenomenon occurring days or weeks after the welding operation. Presence of thermal residual stresses can assist this process. Uniformity in hardness values rule out changes in microstructure as a contributing factor to the failure.

As reported, cracking is seen predominantly in the 20mm thick plates whose strength and hardness as determined is higher than test certificate values and also higher compared to the 18mm thick plates. It has to be noted that hydrogen cracking is strength sensitive, in that, the higher the strength of the metal, the more prone it is to hydrogen cracking. However, the primary cause for cracking in this case is the presence of hydrogen whose origin can be traced to several factors like improper weld surface preparation, improper storage of the welding electrodes, inadequate drying of the welding electrodes etc.

Conclusion: The shell plates of petroleum storage tank sent for investigation have undergone Hydrogen assisted cracking.

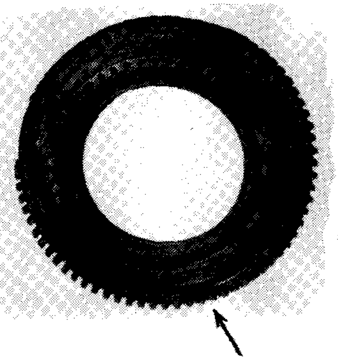

Fig. 12. The LPT blade locking plate region of the low pressure turbine disc.

Recommendations :

(1) The cracked plates have to be rejected
(2) For future welding applications, low hydrogen, dry electrodes should be used.
(3) The weld surfaces should be dry and free from oil, grease, etc.

5.3 Failure of low pressure turbine disc of an aeroengine

5.3.1 Background data : During cyclic spin tests on low pressure turbine disc of an aircraft engine under development, a loud noise was heard when the turbine speed reached around 1200 rpm. This was followed by fire. The drive motor was immediately shut and the fire extinguished. On strip examination, it was found that several components of the turbine disc and fixtures had either fractured or otherwise damaged. These included the disc spinning drive shaft, the dummy roots of LPT disc, the LPT blade retaining plates, the LPT blade locking plate, T headed bolts, Low pressure turbine disc, etc. A detailed analysis of the broken and damaged parts was undertaken to determine the cause of failure.

5.3.2 Observations :

Visual: The drive shaft, a vital component, had fractured at about its mid span. Slight bending of the shaft was seen close to the region of fracture. The fracture surface had a coarse, fibrous appearance and indicated failure by tensile/bending overloads. There was no evidence of delayed failure like fatigue. It was therefore concluded that the failure of the shaft was a secondary and subsequent cause. Similarly, the nature of damages seen on the other components listed above indicated that they were all secondary in nature. The center of focus therefore shifted to the LPT blade locking plate region shown in Figure 12. It could be seen that the region which had suffered minimum damage was the locking plate region (arrow in Fig. 12). The two mounting studs were found pulled outward and sheared along with the locking plate. But for this, the region showed no other damage. Since this region was of interest, further investigations were concentrated in this region. The two studs were extracted by using spark erosion machining and the studs were subjected to scanning microscopy, hardness determination and dimensional measurements.

5.3.3 Scanning Microscopy: The fractured studs extracted from the disc were cleaned and observed under a scanning electron microscope. Elongated dimples were seen on the fracture surface indicating that the studs had fractured by shear loads.

5.3.4 Hardness: Hardness of the damaged stud and damaged blade locking plate were measured and the values were compared with those measured on an unused stud and unused locking plate of the same material. While the damaged stud and damaged blade locking plate showed hardness values of 325 and 375 VHN (at 500 gm load) respectively, the corresponding values for the unused stud and locking plate were 460 and 455 VHN.

5.3.5 Dimensional measurements and design discrepancies: The lengths of the extracted screws (studs) were measured and found to be less than those of unused screws (studs). Similarly, some discrepancies were found in the design of the locking plate as compared to specifications. The locking plate used in this disk is of uniform thickness of 1.8mm whereas design specifies a thickness of 3mm over a width of 19.8mm

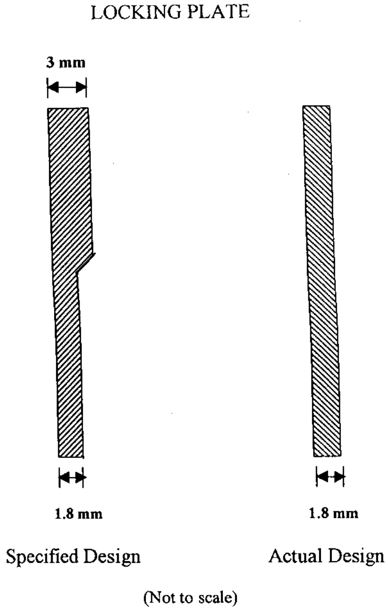

Fig. 13. The specified design and actual design of the locking plate.

and 1.8mm over the rest of the width (Fig.13). Drawing also specifies counter sinking on one side only while the actual plate was counter sunk on both sides.

5.3.6 Discussion : The above observations indicate that the center of focus is the LPT blade locking plate region since fractures/ damages in all the other components studied appear to be secondary in nature. It is probable that the first in the event of failure was the dislodgment of the LPT blade locking plate area from its position because of the shearing of the screws holding it under the centrifugal force of rotation and the blades thrust. Once the locking plate is not in position, it is possible for the adjacent dummy blades to slide out of their fir tree mountings and cause the other damages observed, including the jamming of the rotating mechanism leading to the breakage of the shaft.

An insight into the probable reason for the failure of the locking plate can be obtained by considering the locking plate design and also the strength of the screws used to hold it in position. It can be seen that the locking plate in the present case is of uniform thickness of 1.8mm whereas design specifies a thickness of 3mm over a width of 19.8mm and 1.8mm over the rest of the width. Drawing also specifies countersinking on one side only while the actual plate is counter sunk on both sides. The total length of the locking screw should be 10.5mm. The length of the hole drilled in the disc to accommodate the screw is 6.6mm. With this design, with a locking plate of 3mm thickness and a tab washer of 0.914mm thickness, it can be seen that the stud can be screwed in completely to hold the locking plate in position. However, when the locking plate is only 1.8mm thick, as is the case presently, a gap of 1.2mm is left. Since the screw was tightened completely, this gap was perhaps made up by grinding the bottom of the screw to this extent. The extracted screw (stud) did show grinding marks at its base to substantiate this observation. This means the plate is held effectively by a smaller length of screw. The locking plate of 1.8mm thick and counter sunk on both sides, had a bearing on the screws only to a thickness of 0.8mm which is also the pitch of the threads. Also, the hardness of the screw as measured is considerably lower than a new screw which in effect means lower strength. Since the fire was supposed to be for a short time and since the screw embedded inside the disc would not have come into direct contact with the fire, the reduction in hardness of the screw is unlikely to have been caused by the fire which was post failure.

5.3.7 Conclusion : It is probable that the LPT blade locking plate would have come out due to the shearing of the screws holding it in the outward direction. The dislodgment of the locking plate would have led to the further damages seen. The dislodgment can be attributed to factors related to non adherence to design drawings. The problem is aggravated by the lower strength of the screw.

5.3.8 Recommendations :

(1) Use of LPT blade locking plate of uniform thickness has to be reviewed in the light of design specifications which recommends a locking plate of variable thickness.

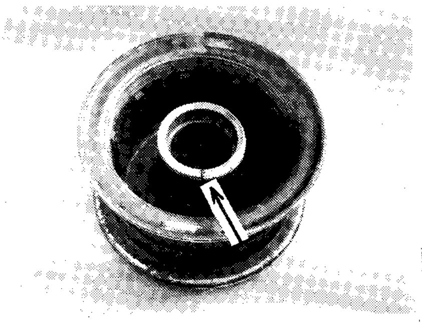

Fig. 14. The cracked main wheel hub.

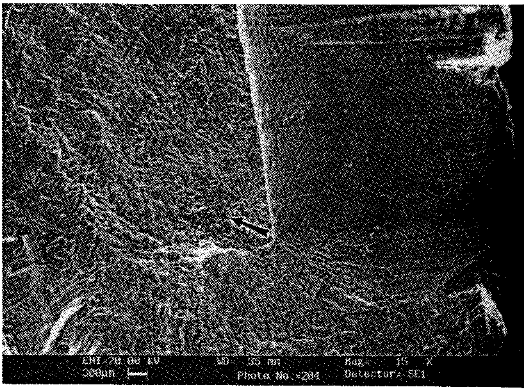

Fig. 15. The scanning fractograph of the fracture surface close to the threaded fastener hole undercut. Striations confirm fatigue fracture. Arrow indicates the direction of crack growth.

(2) Confirm whether the studs (locking screws) and the locking plates have been heat treated to the required specifications.

5.4 Failure of main wheel hubs of a fighter aircraft due to fatigue

5.4.1 Background data : Main wheel hubs form part of the aircraft landing gear system. In an incident, while the aircraft was being taxied, it was observed that the engine rpm required for this purpose was much more than normal. After switching off, the aircraft was jacked up and the hub was found cracked on wheel removal. The cracked main wheel hub was received at NAL for determining the cause of failure. It was reported that the wheel hubs were on life extension of 50 landings from TBO life of 1000 landings.

5.4.2 Observations :

Visual: Fig 14 shows the cracked wheel hub received for investigation. Observations visually and under a stereo binocular microscope showed well defined half moon shaped regions, called beach marks, typical of fatigue at the top region of the hub. This suggests that the crack had initiated at the top region of the hub and progressed inward leading to final fracture near the base of the cylinder.

Scanning Microscopy: The fracture surface was cleaned ultrasonically and observed under a scanning electron microscope to identify the origin of crack initiation. The scanning fractograph of the fracture surface close to the threaded fastener hole undercut is shown in Fig 15. Striations confirming fatigue are seen. From the orientation of the striations it could be seen that the crack had initiated at the sharp corner of the fastener hole undercut (the stress concentration point) and progressed radially outward (shown by arrow in Fig 15).

5.4.3 Discussion : Visual and scanning fractographic features clearly indicate fatigue as the cause of cracking of the wheel hub. The fatigue crack has initiated at a point of stress concentration (at the sharp corner of the undercut) and progressed radially outward. As the crack progressed, it got opened at the outer surfaces of the hub resulting in two independent cracks, one progressing towards the top surface where the gear is attached, while the other progressing downward. In the fractured hub the fatigue crack was found to cover almost the entire length of the inner cylinder indicating its progression over a considerable period of time. This suggests the possibility that a fatigue crack was present in the component even at the time life extension was contemplated.

5.4.4 Conclusions

(1) The wheel hubs have failed by fatigue
(2) The cracks have initiated at the sharp corners of the fastener hole undercut provided for the gear attachment.
(3) In the fractured hub, the fatigue crack growth was found to cover almost the entire length of the inner cylinder before final fracture. This suggests the possibility that the cracks have initiated well before the completion of 1000 landings.

5.4.5 Recommendations

(1) Inspect all the wheel hubs in aircrafts of this batch in the fastener hole regions for presence of cracks
(2) Avoid excess tightening of the fastener

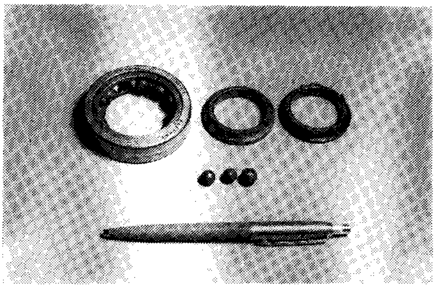

Fig. 16. The failed center support bearing of a jet engine.

5.5 Failure of center support bearings of a jet engine

5.5.1 Background data : Damaged center support bearings (Fig.16) removed from a jet engine were analysed to determine the cause of failure. The ball bearings were both of the single row, deep groove type with split inner rings and a cage. The cage is made of aluminium bronze. The rings and the balls are made of a steel equivalent to 52100 bearing steel. These bearings were mounted side by side in the jet aircraft engine.

5.5.2 Observations

Visual: Visual examination showed that both the bearings were severely damaged. In one of the bearings the inner ring had broken into pieces while the other had suffered severe plastic deformation. It was also observed that all the balls had suffered severe rubbing and some of them showed considerable flattening. The cage had also suffered considerable damage. The material of the cage- Al Bronze- was found embedded on the balls. There was also smearing of aluminium bronze on some portions of the outer ring. It was also found that the ball bearing race had damaged mainly on one side indicating a thrust in that direction.

Metallography: Metallographic examination of the outer ring showed tempered martensite structure with spheroidal carbides. This indicates tempering in the region of around 600^0C. The inner ring and balls revealed fine and coarse pearlite with carbide dispersion.

Hardness survey: Hardness surveys were conducted on the inner and outer rings of the broken bearing as also on the balls. The hardness of the inner ring and the ball averaged RC 37 while that of the outer ring was RC 42.

5.5.3 Discussion : Metallographic examination and hardness surveys indicate that the ball and inner ring of the bearing have seen temperatures above 825^0C, the Acm temperature. For a microstructure with pearlite and cementite network to appear in this type of steel (carbon about 1%), it is necessary to heat it to a temperature of around 850^0C. This is also indicated by the drop in hardness to RC 37. Since the specified hardness of these parts is around RC 60, the fall in hardness is attributed to overheating of these parts.

The fact that the ball bearing race had shown damage on only one side indicates a directional thrust. This is probably due to misalignment of the bearing and shaft. The uneven wearing seen in the ball pockets of the cage also indicate misalignment. Such misalignment might have caused severe stressing of the cage material leading to overheating and fracture.

5.5.4 Conclusion : The bearing has failed by overheating as a result of a possible misalignment of the bearing and the shaft. Insufficient lubrication coupled with high speeds would have aggravated the problem.

5.5.5 Recommendations

(1) Check for misalignment between the bearing and the shaft
(2) Check whether the bearing is lubricated properly

6. CONCLUSION

From what has been said above, it is obvious that a properly conducted failure investigation will reveal

- Deficiencies in design
- Material Imperfections
- Fabrication Defects
- Improper Processing
- Errors in Assembly
- Service Abnormalities
- Inadequate or improper maintenance
- Unintended or inadvertent factors

It is only through systematic analysis of service failures that the real cause or causes for the failure of a component or the sequences leading to an accident be determined and remedial measures initiated to prevent the recurrence of the same. Performing failure analysis is a challenging and exciting job but for the exercise to be fruitful and rewarding, the application of a proper methodology is a pre-requisite. Though the methodology remains largely the same, it has to be noted that no two failures are similar and that each failure poses problems peculiar to itself. It is therefore necessary for the investigator not merely to have a sound background in the areas central to his analytical work but also to have the knowledge to know when and what experts to call in other fields of specialization that interface with his work. It cannot be overemphasized that the time and money spent in analyzing a failure is more than well spent.

SUCCESS THROUGH DESIGN - PROGRESS THROUGH FAILURE ANALYSIS

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